

ELECTRODYNAMIC TETHER OPERATIONS BEYOND THE IONOSPHERE IN THE LOW-DENSITY MAGNETOSPHERE

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ABSTRACT

In the classical concept for the operation of electrodynamic tethers in space, a voltage is generated across the tether, either by the tether's orbital motion through the earth's planetary magnetic field or by a power supply; electrons are then collected from the ionospheric plasma at the positive pole; actively emitted back into space at the negative pole; and the circuit is closed by currents driven through the ambient conducting ionosphere. This concept has been proven to work in space by the Tethered Satellite System TSS-1 and TSS-1R Space Shuttle missions; and the Plasma Motor-Generator (PMG) tether flight experiment. However, it limits electrodynamic tether operations to the F-region of the ionosphere where the plasma density is sufficient to conduct the required currents—in other words, between altitudes of approximately 200 to 1000 km in sunlight. In the earth's shadow, the ionospheric density drops precipitously and tether operations, using the above approach, are not effective—even within this altitude range.

There are numerous missions that require in-space propulsion in the Earth's shadow and/or outside of the above altitude range. This paper will, therefore, present the fundamentals of a concept that would allow electrodynamic tethers to operate almost anywhere within the magnetosphere, the region of space containing the earth's planetary magnetic field. In other words, because operations would be virtually independent of any ambient plasma, the range of electrodynamic operations would be extended into the earth's shadow and out to synchronous orbit—forty times the present operational range. The key to this concept is the active generation of plasma at each pole of the tether so that current generation does not depend on the conductivity of the ambient ionosphere. Arguments will be presented, based on existing flight data, which shed light on the behavior of charge emissions in space and show the plausibility of the concept.

BACKGROUND

PLANETARY PLASMA ENVIRONMENTS

The near space environment of the Earth is dominated by the planetary magnetic field. The region of closed field lines (those that loop from one pole into space and close back on the earth near the opposite pole) extends into space approximately ten Earth radii, R_E , in the sunward direction (more or less, depending on the level of solar activity) — and somewhat farther in the anti-sunward direction. This means that the boundary between the magnetosphere, containing a significant planetary magnetic field, and the interplanetary solar wind plasma occurs at some 64,000 km. This easily exceeds the altitude for synchronous orbit (42,000 km). By comparison, the bulk of the magnetospheric plasma is confined to a

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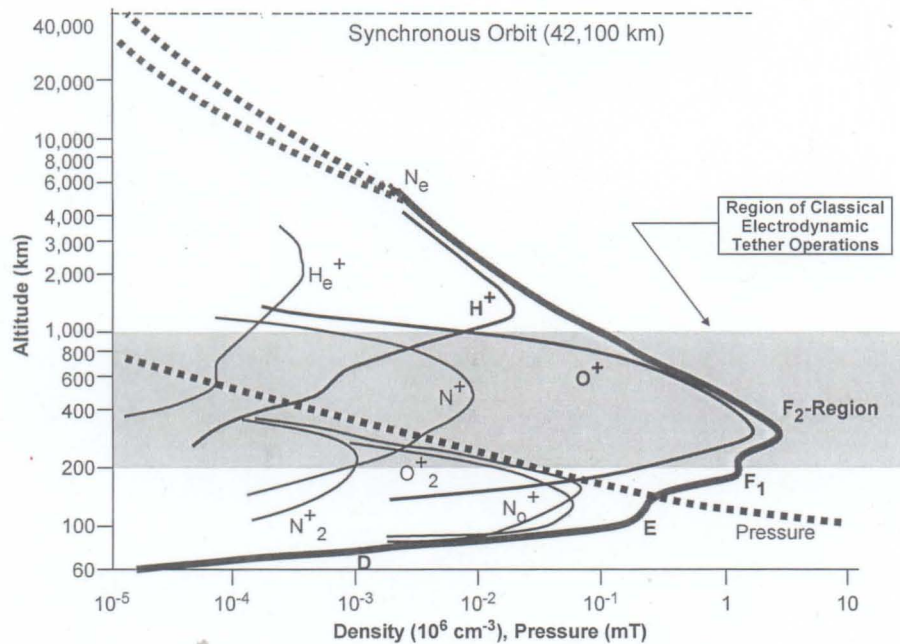


Figure 1. Profile of Plasma Density Showing Peak in the F-Region Ionosphere at Approximately 300 km Altitude. (Plasma Density is Very Low above 1000 km)

relatively thin shell below 1000 km, called the ionosphere (Figure 1). It is the ionosphere to which electrodynamic tether operations have been previously limited. It is the enormous region above the ionosphere, extending from ~1000 km to ~40,000 km, with which we are concerned in this paper. While the planetary magnetic field in this region remains significant (on the order of 3×10^{-4} G at $10R_E$), the plasma is extremely tenuous (densities are in the range of 10 to 100 cm^{-3}) and incapable of carrying any significant electrical current.

CONCEPTUAL DESCRIPTION

If electrodynamic tethers did not have to rely on the ionospheric plasma to close the electrical circuit, they would be capable of generating a propulsive thrust out to the edge of the magnetosphere at ten or more earth radii. More importantly, this would increase the applicability of tethered systems—enabling payloads to be delivered to synchronous orbit with solar-powered, propellantless electrodynamic propulsion. In its application to MXER, electrodynamic reboost would be spread over a greater portion of the orbit, thereby reducing the magnitude of the required tether current to manageable levels. The fundamental question is, “How can an electrodynamic tether operate independent of significant environmental plasma?”

In the case of an electrodynamic tether propulsion system, the ability to operate in a virtually plasma-free environment depends critically on two factors: (1) the ability to emit equal and opposite amounts of charge from the ends of the tether, resulting in current flow in the tether, but no net charge transfer to the system, and (2) the inability of the emitted charge to return to the tether system.

The imposed emf, required to drive the electrical current, will polarize the tether—positive on one end and negative on the other. This will help in the ejection of charge of appropriate polarity from the two ends. In “classical” tether operations, electrons are emitted at the negative end and collected from the ambient plasma at the positive end. In the case of electrodynamic tether operations in regions of extremely low plasma density, each end of the tether will be equipped with a plasma generator. The emitted plasma will provide a highly conducting path for the ejection of charge (positive or negative) into free space from each end of the tether. This is shown schematically in Figure 2.

As shown in Figure 3, once ejected from the tether, the free moving charged particles will become trapped by the planetary magnetic field as their translational, cross-field orbital motion is converted into circular gyrations by the Lorentz force. The tether and its parent spacecraft will, however, leave these regions of trapped positive and negative charge behind as they continue to move along an orbital path around the planet. The regions of electrical charge left in the wake of the spacecraft should eventually spread out along the field lines until, conceivably, they migrate sufficiently to close the circuit. The process by which this closure occurs is of scientific interest, but is not of prime concern to the propulsion application. The key point with regard to the electrodynamically accelerated spacecraft is that the charge has been dumped and is prevented from returning to its emitter by the combined action of the ambient planetary magnetic field and the lack of an attractive potential. Note that, because equal currents of opposite polarity are emitted from its ends, an electrical current will flow in the tether but there will be no *net* charge transfer to or from the total system. The tether and its spacecraft will, therefore not charge to a high potential.

The following description of the basic physics involved in the emission of charge into a vacuum (which is fundamental to the proposed electrodynamic propulsion application) is qualitative and intuitive in places because the conceptual effort is in its infant stages of development. It should, however, provide sufficient insight to show the feasibility of the concept, pending a more systematic and thorough treatment.

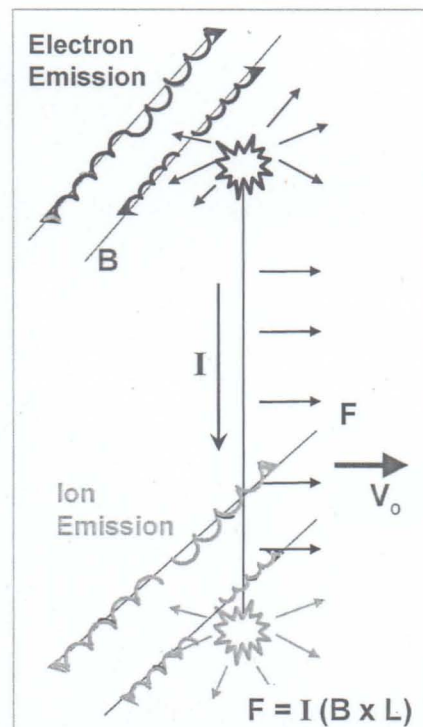


Figure 2. Functional Schematic of Electrodynamic Tether Operations above the Ionosphere

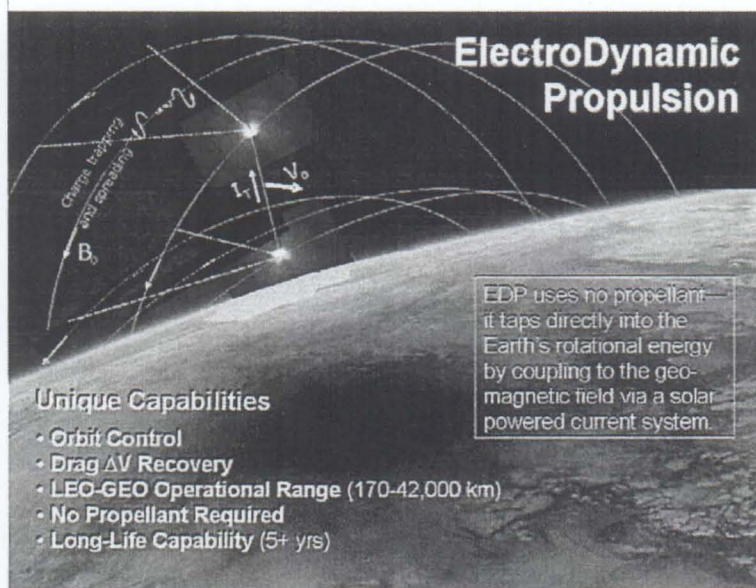


Figure 3. Schematic of High-Altitude Electrodynamic Propulsion in an Ultra-Low Density Plasma Environment above the Ionosphere

FUNDAMENTALS OF CHARGE EMISSION INTO A VACUUM

The effects of thermal motion on the dispersion of a plasma cloud

In the case of an un-biased plasma cloud surrounded by vacuum, the cloud will expand without the help of any tether-imposed electrical bias or ambient magnetic field.

For simplicity, we assume a plasma cloud of spherical geometry to be created at time t_0 in isolation and with internal thermodynamic equilibrium; i.e., in a vacuum environment that initially contains no neutral or charged particles or magnetic or electric fields; and with the thermal energy of all species of particles equal. This cloud will immediately begin to expand radially outward, driven by its thermal energy, according to a process known as the "expansion of plasma into vacuum," or "Collisionless Plasma Expansion" (CPE) in the literature (Samir et al., 1983, 1986).

Conceptually, this process can be perceived as a logical sequence where (1) the more mobile of the charged species (usually electrons) leads the expansion away from the cloud boundary because of its greater thermal velocity; (2) the resulting charge separation, in turn, creates an electric field between the leading front of electrons and the ions left behind at the cloud boundary; (3) the electric field accelerates the ions beyond their thermal speed in the outward radial direction. As the leading electrons give up their energy to the ions, they are apparently replaced, and the electric field maintained, by fresh electrons from the plasma cloud. This process is very robust — it has been observed over an extremely large range of plasma density and should occur anytime a well-defined boundary (in density or temperature) is created in plasma.

CPE was first discovered in the dense plasma of impulsive fusion experiments as a result of its impact on plasma confinement. It has since been observed in steady-state laboratory experiments in which the ions in synthesized low-density space plasma were directly observed to be accelerated across the wake boundary and into the wake void region at speeds significantly above the ion acoustic speed. Moreover, the process is clearly distinguished by the acceleration of the ions by the expansion electric field—as opposed to a constant drift velocity that would result from simple thermal expansion (Wright et al., 1985 and 1986). In a flight experiment, carried out in 1985 on the Spacelab-2 mission, the CPE process was observed to be a governing process in the filling of the wake created by the Space Shuttle Orbiter in the ionospheric plasma (Stone et al, 1988; and Singh et al. 1989). This observation led to the discovery, by the WIND spacecraft in 1994, of CPE in the filling of the wake created by the Moon in the ultra-low density solar wind plasma.

The effect of an electrical bias on charge ejection from a plasma cloud

Although the plasma clouds will expand away from the ends of the tether system, driven simply by thermal energy, the outward fluxes of positive and negative charge in the CPE process are equal and the cloud will remain neutral. However, the addition of the electrical bias produced by the tether can be expected to result in the net expansion of one charge species and, therefore, the emission of an electrical current.

According to Coulomb's Law, two charges in space will exert a mutual force on each other given by

$$F = qq'/(r/r)/(4\pi\epsilon_0 r^2)$$

It is noteworthy that the force between charged particles in inertial space is independent of any wall effects or associated reference potentials and, therefore, applies to the behavior of plasma clouds in free space.

The $1/r^2$ dependence in Coulomb's Law leads directly to Gauss' Law, which describes the relation between the electric field created on any closed surface that encloses a volume containing a net electrical charge. This relation is

$$\epsilon_0 \oint_S \mathbf{E} \cdot \mathbf{n} \, da = \int_V \rho \, dV$$

where the integral on the LHS is over the closed surface having a radial electric field, E , and that on the RHS is over the enclosed volume containing a charge density, ρ . For simplicity, we will take the closed surfaces to be spherical and, since electron emission is better understood, we will consider the ion emission process at the positive end of a tether equipped with a plasma generator.

Using Gauss' Law, it is straight forward to show that a given electric field, E , produced at the surface of a small spherical electrode at one end of a tether requires a surface charge density, σ , on the electrode. This, in turn, implies the presence of a number of charges, N which are supplied by a redistribution of charge in the tether. Once this has occurred, the electrode will be biased and no current will flow in the tether unless the charge on the electrode is emitted or neutralized—in which case it would be replaced by a further redistribution of charge (current flow) in the tether.

The question now is, "How does the surrounding plasma cloud react to the presence of the biased electrode?" In attempting to neutralize the charge on the electrode, either N ions must be ejected from the electrode surface, or N electrons must be supplied to the surface by the plasma cloud. The latter requires the least energy and will, therefore, be the preferred process. This will create an ion-rich shell in the plasma immediately adjacent to the electrode. Once again, using Gauss' Law, it can be shown that this excess charge, created by the biased electrode, is translated to the outer surface of the plasma cloud. In the classical view of electrodynamic tethers, the excess charge would then be absorbed by the ambient conducting plasma. However, since, in this case, we assume the cloud to exist in vacuum, no ambient electrons are available.

The excess charge at the cloud surface will, according to Gauss' Law, produce a radial electric field $E_r = \sigma/\epsilon_0$, where $\sigma = eN/4\pi R^2$ is the surface charge density at the cloud boundary ($r = R$). The free ions at the surface of the plasma cloud will, therefore, experience an electric field that will accelerate them radially away from the cloud. At this point, since the process is conceptually frozen in time, the cloud is again neutral—we are considering only the reaction of the cloud to the initial N charges placed on the electrode. The excess charge now resides in a shell that has expanded beyond the cloud surface to some distance, $r > R$. What happens to this shell? Again, applying Gauss' Law, a radial electric field, $E_r = eN/4\pi r^2$, exists that, although decreasing with r , will continue to accelerate the shell of ions radially outward indefinitely.

Now we must consider what happens when this process is allowed to progress in time; i.e., an electrical current is driven through the tether and replaces charge that has been neutralized on the electrode. Obviously, the initial plasma cloud would quickly dissipate—electrons being absorbed by the electrode and ions being accelerated into space. The limiting factor will, therefore, be the rate of ionization of neutral gas, dn/dt , within the cloud. In order for ionization to occur, electrons must be accelerated above the ionization energy of the neutral gas—typically about 15 eV. The electrode, therefore, must be biased to several tens of volts. We assume 50 to 100 volts. The emitted current density, $j = env/4$, will then be governed by the continuity equation for ions,

$$dn/dt + nv = 0,$$

where dn/dt is the ionization rate. The total current ejected from the cloud, $I = jA$ is then obtained by applying these relations to the entire cloud volume.

Ionization is a complex process that depends on a number of factors, including the magnitude of the emitted current and the type of discharge ignited (Holt and Haskell, 1965). However, hollow cathodes have been shown to be capable of emitting currents on the order of amps at a few tens of volts bias. More recently, solid expellant plasma generator devices have been shown to have similar emission characteristics (Burner and Wilbur, 1999, Stone 2005). We can, therefore, reasonably expect the generic plasma cloud, taken in this case to exist at the positively biased end of the tether, to exhibit similar characteristics.

Effects of the geomagnetic field on the dispersion of the emitted charge

Clearly, an ambient magnetic field is not required to emit charge from a spacecraft if the emitted positive and negative fluxes are equal. However, an electrodynamic tether will generate thrust only in the

presence of such a field; i.e., $\mathbf{F} = i(\mathbf{B} \times \mathbf{L})$, and since an ambient B-field is required, its effect on particle dispersion is important. As indicated below, this addition to the above problem will generally tend to enhance charge dispersion.

To indicate the type behavior expected when the plasma cloud is immersed in an ambient magnetic field, we have performed some rudimentary calculations that are illustrated in Figures 4-7. Figure 4 gives the geometry. The orbit lies in the xz-plane with the orbital velocity parallel to the x-axis. The B-field is taken to lie in the xy-plane at an angle, θ , to the x-axis. The charged particles are emitted from the origin in the xz-plane at an angle, ϕ , to the x-axis.

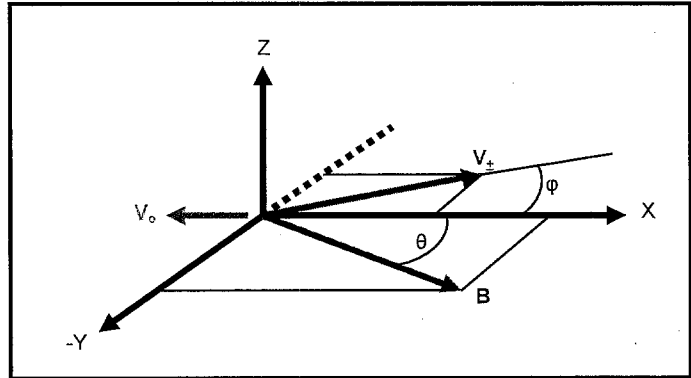


Figure 4. Particle Emission Geometry

Figure 5 shows several example ion trajectories. Curves are shown for 50 and 100 eV ions emitted along the x-axis for cases where the B-field is inclined 60° and 90° to the xz-plane. In all cases, the ions escape and do not return to the point of emission.

Figures 6 and 7 show example electron trajectories. In Figure 6, the electrons are emitted along the x-axis for the case where B is normal to the x-axis. This special case results in pure gyroscopic motion which, because $v_e \gg V_0$, brings the electrons back almost to the point of emission. However, when ejected at an inclination of only a few degrees, to the xz-plane (and, therefore B) the high speed of the electrons results in a significant component along B, which carries them rapidly away from the origin, as shown in Figure 7.

Plot of Ion Distance from Voltage Source
versus Time
(xy-plane angle = 0 deg)

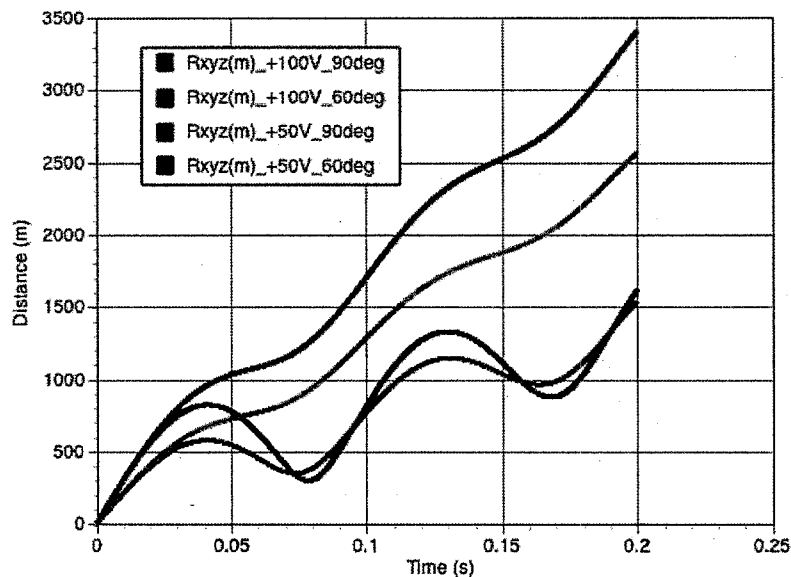


Figure 5. Trajectories of Ions Emitted from the Plasma Cloud into an Ambient Magnetic Field for the Case Where the Initial Velocity of the Ions is Parallel to the X-Axis. The Inclination of the B-Field to the Velocity Vector and Bias on the Kinetic Energy of the Ions, in eV, are as Indicated in the Figure.

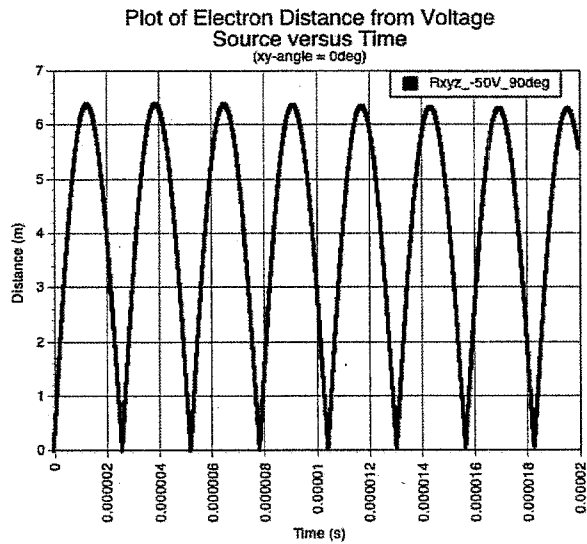


Figure 6. Trajectories of Electrons Emitted from the Plasma Cloud into an Ambient Magnetic Field for the Case where the Initial Velocity of the Electron is Aligned with the Orbital Velocity Vector. The Inclination of the B-Field to the Velocity Vector is 90 Degrees and the Kinetic Energy of the Electrons is 50 eV.

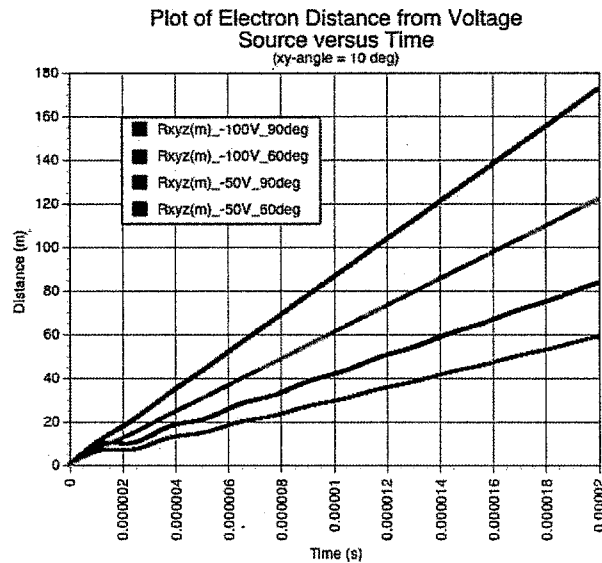


Figure 7. Trajectories of Electrons Emitted from the Plasma Cloud into an Ambient Magnetic Field. The Initial Inclination of the Electron Velocity to the Orbital Velocity Vector is 10 Degrees. The Inclination of the B-Field to the Velocity Vector is 60° and 90°, as Indicated for the Various Cases. In Addition, Curves are Given for 50 and 100 eV Electrons.

SUPPORTING DATA

It has been verified, by in-space operations, that charge can be accelerated away from a spacecraft provided an equal and opposite charge is also emitted. For example, in the case of ion propulsion, a high-energy positive ion stream can be emitted only if an equal current of electrons is emitted from a "neutralizer." Typically, the neutralizing electrons are emitted directly into the stream of accelerated ions, as in the case of the Deep Space-1 NSTAR ion propulsion engine. However, this is not necessary. In principle, the neutralizer can operate from any point on the spacecraft so long as it is in electrical contact with the ion accelerator. This was demonstrated by charging control experiments carried out on the ATS-5 and ATS-6 satellites in synchronous orbit. In this case, charging occurred over the surface of the satellites but neutralization was accomplished by single emissive filaments (Olsen, 1985). In the context of the above discussion, the tether is, in essence, a long spacecraft.

The primary difference between the standard operation of an electrodynamic tether within the confines of the dense ionospheric plasma, as opposed to operations in the outer magnetosphere, is that electrons can be *collected from* the existing ionospheric plasma on the positive pole without the need for ionization and injection of an expellant; whereas, in the very low-density plasma environment above the ionosphere, the system must *create and inject* its own plasma into the region around the positive pole in order to *emit* positive ions *into* the environment. (This is similar to the process of electron emission at the negative pole under standard operations.) Operations above the ionosphere will, therefore, be somewhat less efficient. However, in exchange for some loss of efficiency, the range of operations, as discussed above, is extended by more than an order of magnitude.

APPLICATION TO ORBITAL TRANSFER

Initial rough-order calculations indicate that a 20-km long electrodynamic tether conducting 10 amps of current would be able to move a 500 kg satellite from 300 km to synchronous orbit in less than 6 months. The energy required to drive the system would be provided by the sun, with the expellant for the contactor emissions being the only expendable required. This results in extremely high ISP values, or mass utilization efficiency. (The ISP values for electrodynamic propulsion are termed "effective" to indicate the use of an expellant, which is a low-energy charge carrier in the plasma discharge, as opposed to the propellant that is accelerated to high energies to create thrust in rocket engines.) The range of ISP associated with various in-space propulsion technologies is shown in Figure 8.

The mass of the emitted ions required for the transfer, and the resulting effective ISP, are shown in Case-1 of Table 1 for a standard xenon hollow cathode contactor and for a solid expellant plasma source (SOLEX) being developed by SRS that uses a lighter hydrocarbon expellant material (Stone, 2005). These calculations do not include ionization efficiency. As shown in the table, tether length and current can be varied to obtain shorter transfer times or, alternatively, a lower expellant requirement. For example doubling either the current or tether length with respect to Case-1 (Cases 2 and 3, respectively) reduces the transfer time for the above case to less than 3 months. Although ISP is a function of tether length only and does not change significantly between Cases 1 and 2, the more rapid transfer reduces the "burn" time and is achieved with no significant change in the expellant mass requirement (actually, there is a

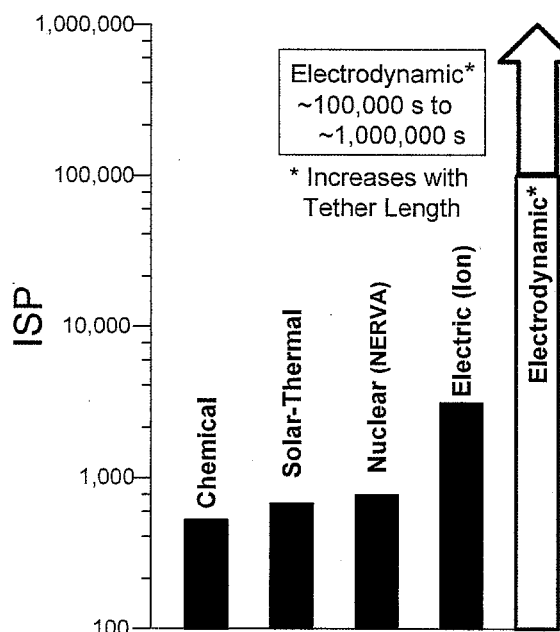


Figure 8. Expelled Mass Efficiencies (ISP) for Various in-Space Propulsion Technologies

decrease of 4-percent). When the current is not increased, but tether length is doubled (Case-3), the transfer time with respect to Cases 1 is, again, cut in half but with a 52-percent reduction in the required expellant mass. Cases 5 and 6, for a 4000 kg payload mass, show the possibilities for transferring the largest Boeing 702 satellites. Once on synchronous orbit, the tether system can either be jettisoned or retained to provide some degree of gravity-gradient stabilization.

The electrodynamic tether propulsion system possesses the inherent flexibility to provide efficiencies and transit times that appear to be competitive with, or superior to, those achieved by ion propulsion. For example, using the parameters for the Deep Space-1 NSTAR ion propulsion system, which has an ISP of about 3000 s, the transfer of a 486-kg satellite to synchronous orbit would require 9.3 months and 34.1 kg of xenon propellant (also neglecting ionization efficiency losses). The electrodynamic transfer is Case-3 of Table 1 is accomplished almost seven months faster while requiring about three times the expellant mass for a standard xenon contactor, but only seven percent of the mass if the SOLEX plasma source under development by SRS Technologies is used. This represents an effective ISP of 1,377,214.

Although specific in-space propulsion applications may differ from LEO-to-GEO transfer, this example demonstrates the general effectiveness of electrodynamic propulsion above the ionosphere in the low-density magnetosphere. If LEO-GEO transfer can be achieved with ED propulsion, then so can orbit control or modification for other purposes; including (1) raising the orbit of valuable space assets such as the Hubble Space Telescope to a high parking orbit (permitting future reactivation) rather than disposing of it in the Pacific Ocean, and (2) the periodic reboost of the proposed MXER in-space boost facility that requires the propulsive electrodynamic force be applied over a significant portion of its elliptical orbit to keep the required tether current at physically achievable levels.

Table 1. Preliminary of Transfer Time Calculations using ED Tether Propulsion

Case #	Sat. Mass (kg)	Tether Length (km)	Tether Current (A)	Final Distance (R_E) ¹	Transfer Time (Mo.)	Ionized Expellant Mass ² (kg)		Effective ISP ⁵ (s)	
						Contactor ³	SOLEX ⁴	Contactor ³	SOLEX ⁴
1	500	20	10	6.63	5.4	190	4.6	16,663	688,268
2	500	20	20	6.45	2.6	182	4.4	16,862	697,856
3	500	40	10	6.63	2.6	91	2.2	33,295	1,377,214
4	4000	20	10	6.40	41.4	1454	35.5	16,598	679,831
5	4000	100	10	6.66	8.8	309	7.6	82,920	3,373,556

1 Synchronous orbit = 42,095 km = 6.6 R_E .

2 Ionized mass only—does not account for ionization efficiency (typically 10%)

3 Assumes Xe gas expellant ($M_{Xe} = 131$ AMU)

4 Hydrocarbon with C:H = 1:4 ($M_C = 12$ AMU, $M_H = 1$ AMU)

5 No propellant used. "Effective ISP" is based on average *expellant* usage, which changes with increasing r .

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